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par

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CONTRIBUTION A L'ETUDE DE LA CONVECTION THERMIQUE

PULSEE AUTOUR DES CYLINDRES

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Soutenue le 28 Octobre 1969, devant la Commission d'examen

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HEAT AND MASS TRANSFER IN FLOWS

WITH SEPARATED REGIONS

Heat transfer by pulsating air flow around cylinders

M. Martin and J. Gosse

September 1 - 13 - 1969

Herceg Novi — Yugoslavia

GENERAL SYMBOLS

C_p	:	specific heat at constant pressure
D	:	cylinder diameter
f	:	pulsating frequency
k	:	thermal conductivity
Nu_θ	:	local Nusselt number
Nu_g	:	global Nusselt number
T	:	temperature
T_s	:	temperature at the wall
T_∞	:	free stream temperature
$\bar{U}_\infty$	:	mean free stream velocity
U_f	:	velocity in the steady potential flow
$\tilde{U}_p$	:	instantaneous velocity in the pulsating potential flow.
u, v	:	velocity components on x and y axis
x	:	distance from de stagnation point measured along the cylinder contour
y	:	distance measured at right angle to the cylinder wall
α_θ	:	local coefficient of heat transfer.
β, γ	:	first two terms of the Blasius series
ΔT_o	:	$T_s - T_\infty$
ΔT	:	$T - T_\infty$
ϵ	:	factor of pulsation amplitude
ν	:	kinematic viscosity
ρ	:	density of the air (mass per unit volume)
τ	:	pulsating rate $\epsilon = \tau \sqrt{2}$
ψ	:	stream function
ω	:	pulsating circular frequency
T^*	:	reduced temperature : $T^* = \frac{T - T_\infty}{T_s - T_\infty} = \frac{\Delta T}{\Delta T_o}$
x^*, y^*	:	reduced co-ordinates : $x^* = x/D, y^* = y/D$
η	:	reduced parameter : $\eta = y \sqrt{\frac{\bar{U}_\infty}{D\nu}}$
λ	:	reduced frequency : $\lambda = D \omega / \beta \bar{U}_\infty$

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M. MARTIN and J. GOSSE. Laboratoire de Mécanique ENSEM (*)

During the last few years, one has noticed in the field of fundamental and applied research an increased interest in the study of the phenomena of heat transfer between a body and an instationary flow.

The types of flow often studied have a velocity varying periodically as a function of time.

One may distinguish among these latter

- the vibrating flows : for example a sound field with sinusoidal modulation and weak amplitude.
- the pulsating flows whose pulsations can attain great amplitudes without reversal flow.

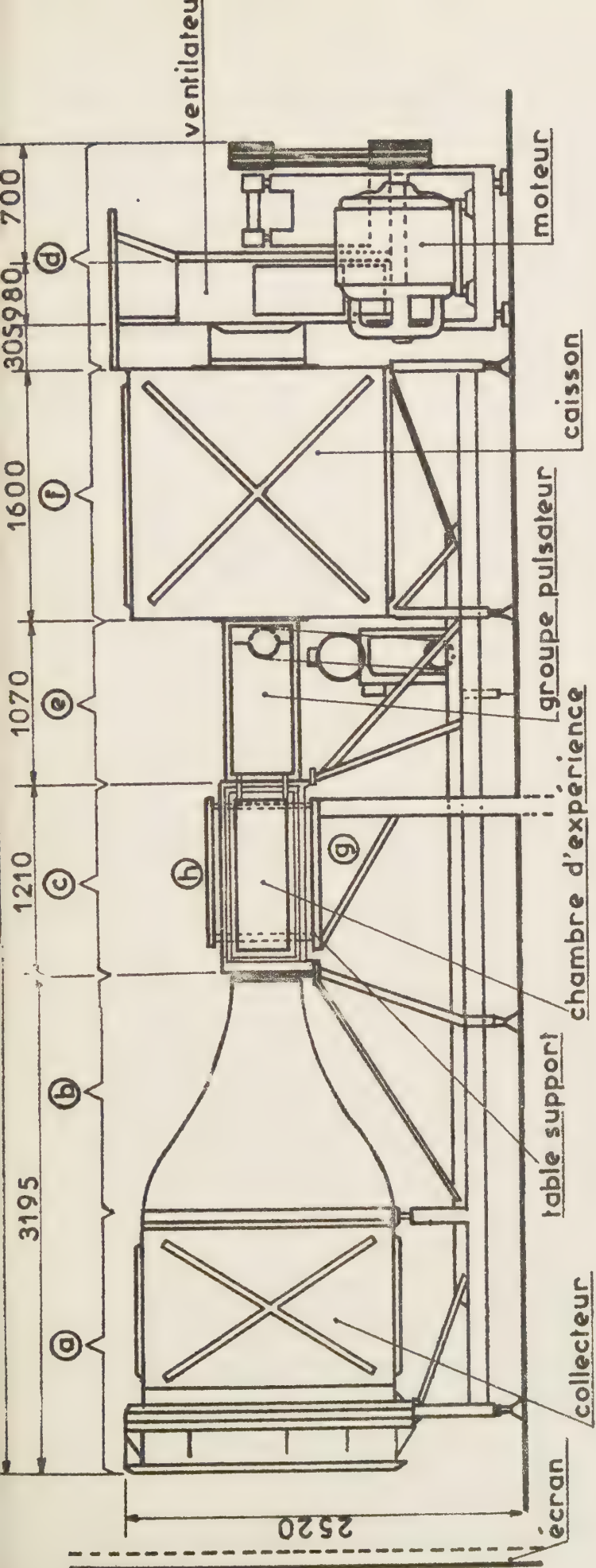
The aim of this communication is to analyse the action of a pulsating flow of low frequency on the separated boundary layers and wakes which develop on the surface and behind an obstructing cylinder placed perpendicular to the flow direction.

1 - PULSATING WIND-TUNNEL - FLOW CHARACTERISTICS

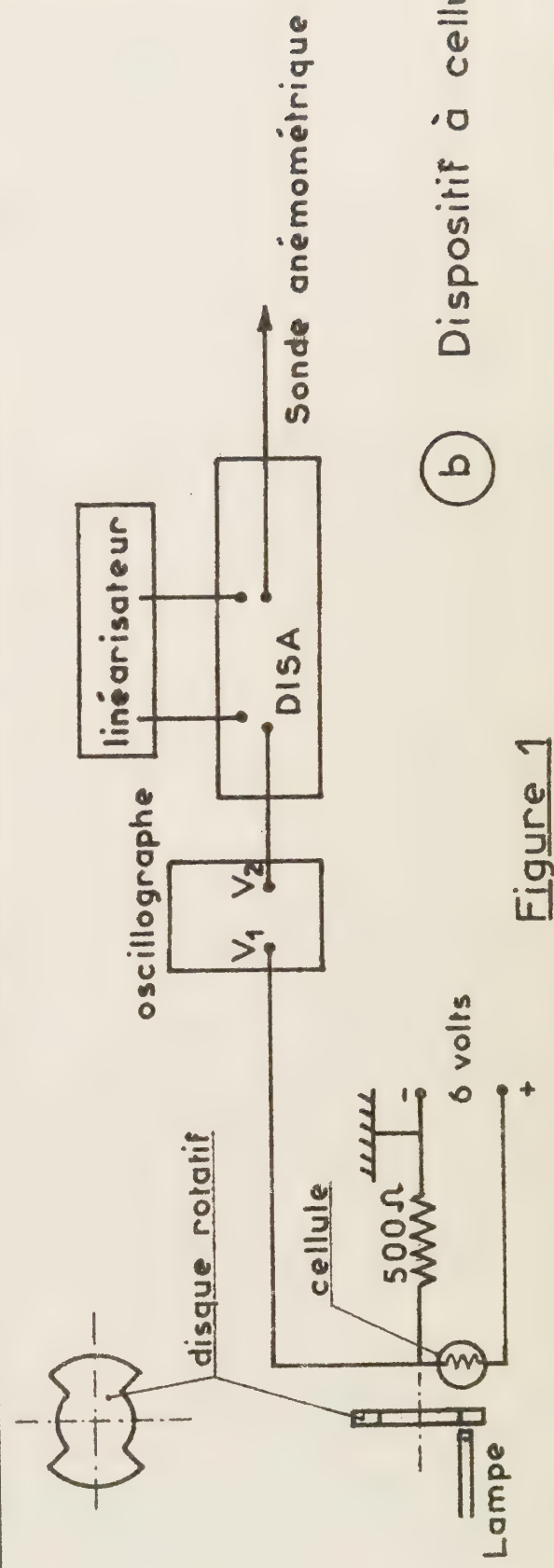
The components of the pulsating wind-tunnel used are those of the standard wind-tunnel (fig. 1, a) air collector (a), convergent section (b), 400 x 400 mm squared test section (c), motor-fan unit (d), but differs in that it has a pulsating generating set (e) and a caisson (f) placed between the tunnel test-section and the motor-fan unit.

The pulsating system consists of four rectangular, interchangeable shutters turning in phase around four parallel, horizontal shafts and driven by a chainbelt. A motor drives the unit by using a belted speed-variator permitting

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a - Soufflerie à air pulsé - Plan d'ensemble - Echelle : 1/40 -



b Dispositif à cellule

Figure 1

modification of the frequency from 10 to 50 Hertz. An electronic device with a photoelectric cell (fig. 1, b) signals the instant of complete closing of the tunnel. As for the calsson, its function is to smooth over the pressure fluctuations.

In the generating conditions of temperature and pressure T_{∞} and p_{∞} the velocity signal inside the test section is measured with the aid of an anemometric probe which reveals a law of the form :

$$\tilde{U}_{\infty} = \bar{U}_{\infty} [1 + \sqrt{2} \tau \sin 2 \pi f t]$$

The flow is characterized by the mean velocity $\bar{U}_{\infty}$, the pulsating rate τ defined as the root mean square value of the fluctuating velocity component, the pulsating frequency f . These three parameters can vary only within the following limits :

$$5 \text{ m/s} \leq \bar{U}_{\infty} \leq 20 \text{ m/s}$$

$$0 \leq \tau \leq 40 \%$$

$$10 \text{ Hz} \leq f \leq 50 \text{ Hz}$$

II - LOCAL HEAT TRANSFER BY PULSATING AIR FLOW

II - 1 - Cylinders permitting local measurements : D = 45 mm (figure 2)

The cylinder L2 (a) is equipped at its center with a global heating device which heats the thick copper tube owing to an electrical resistance in close contact with the inside surface ; the local measuring element consists of a cylinder sector punched out radially along two generating lines and keyed to the main body of the cylinder with the aid of two isolating rods. It is composed of a heating resistance R_0 which covers the bottom of the groove and of a thermocouple T_0 , the whole packed in tin.

Auxiliary components situated on either side of the local measuring element serve as compensatory elements (b) and (c) ; they each include one thermocouple and one resistance destined to minimize the conduction heat losses. Slits in the cylinder's thickness diminish the conduction heat losses in the other parts of the cylinder.

Technical drawing of a rectangular plate. The overall height is 240 and the overall width is 57. The plate features a central horizontal slot and is flanked by two hatched regions.

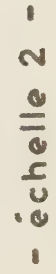


Figure 2

The resistance are fed by independent heaters with voltage-regulators. The electrical powers supplied are determined by reading the amperemeters and voltmeters.

Through action upon the heaters at the center R_0 , of the measuring element R_0 , and of the compensatory components R_1 and R_2 , the heat balance is attained for an angular position θ of the measuring element.

The local heat transfer is characterized by :

$$\alpha_{\theta} = \frac{P - \varphi_p}{s \cdot \Delta T_0} \quad \text{and} \quad Nu_{\theta} = \frac{D}{sk_f} \frac{P - \varphi_p}{\Delta T_0}$$

where p is the power supplied at R_0 and φ_p represents the estimated radiation and conduction losses.

11 - 2 - Experimental determination of the local heat transfer :

The curves in figures 3 and 4 summarize the effects of the velocity pulsations at the surface of the obstructing cylinder. Two factors appear which seem to have a considerable influence on the increase of local heat transfer ; these are : the pulsating rate and the pulsating frequency.

11 - 2 - 1 - Influence of the pulsating rate for $f = 20$ Hz

Figure 3 shows the very localized and specific effect of the pulsations. On the surface of the cylinder, two zones can be distinguished :

a) - On the forward face : $0 \leq \theta \leq 80^\circ$: where the boundary layer is laminar with a negative pressure gradient, the pulsations continue to have no noticeable effect on the heat exchange at the wall. We notice however a light dispersion near the stagnation point, but the evolution of the turbulence intensity as a function of the pulsating rate can explain, according to the studies of J Kestin and R.E. Mer [1] , the recorded differences.

The experimental results are in perfect agreement with the theoretical study summed up in Appendix 1 concerning the laminar boundary layers in a pulsating flow ; the pulsations prove to have no noticeable effect on the heat transfer.

Influence du taux de pulsation sur l'échange

$\bar{U}_\infty \approx 7,25 \text{ m/s}$ $Re \approx 20000$

$f = 20 \text{ Hz}$

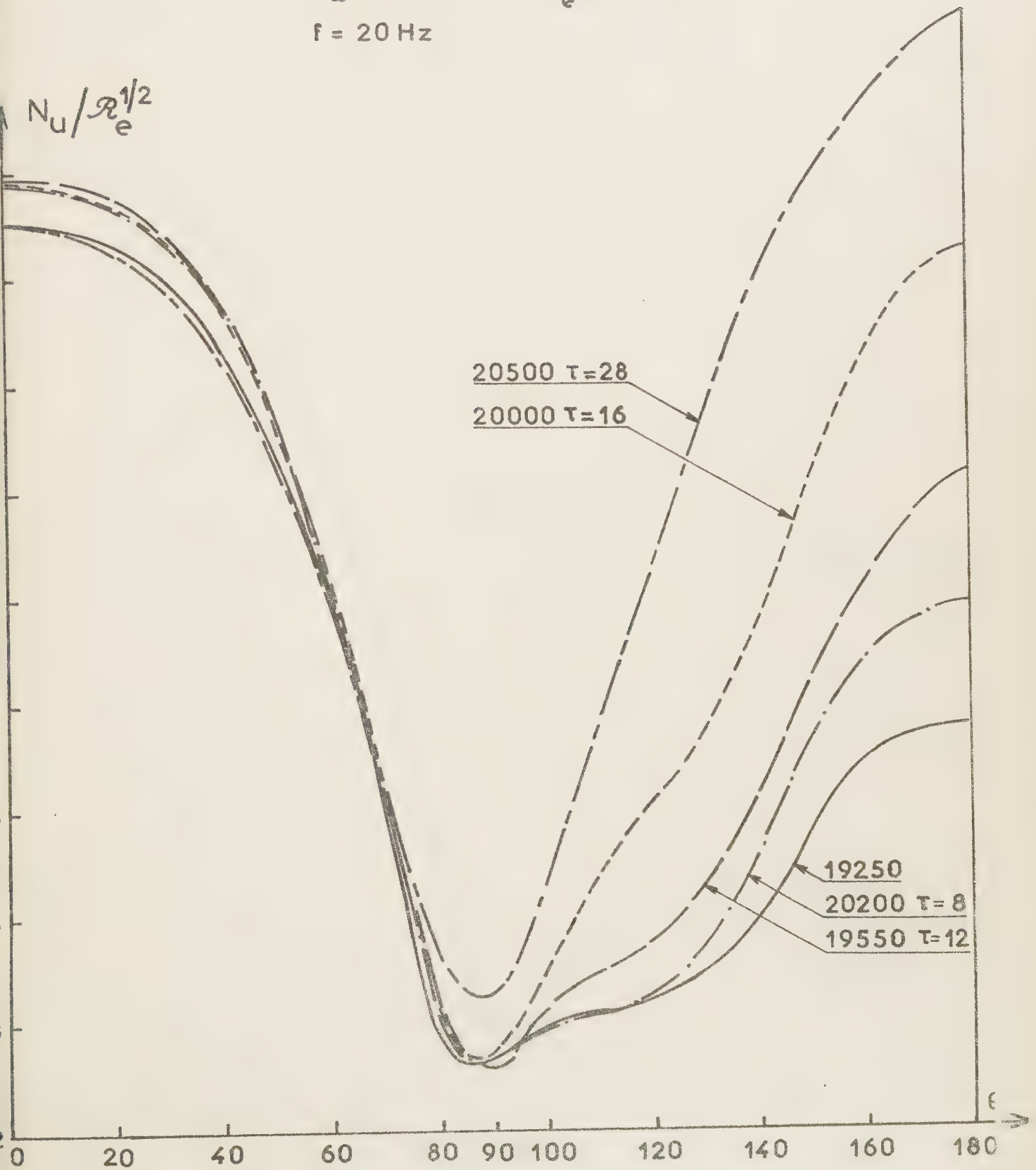


Figure 3

Influence de la fréquence sur l'échange local

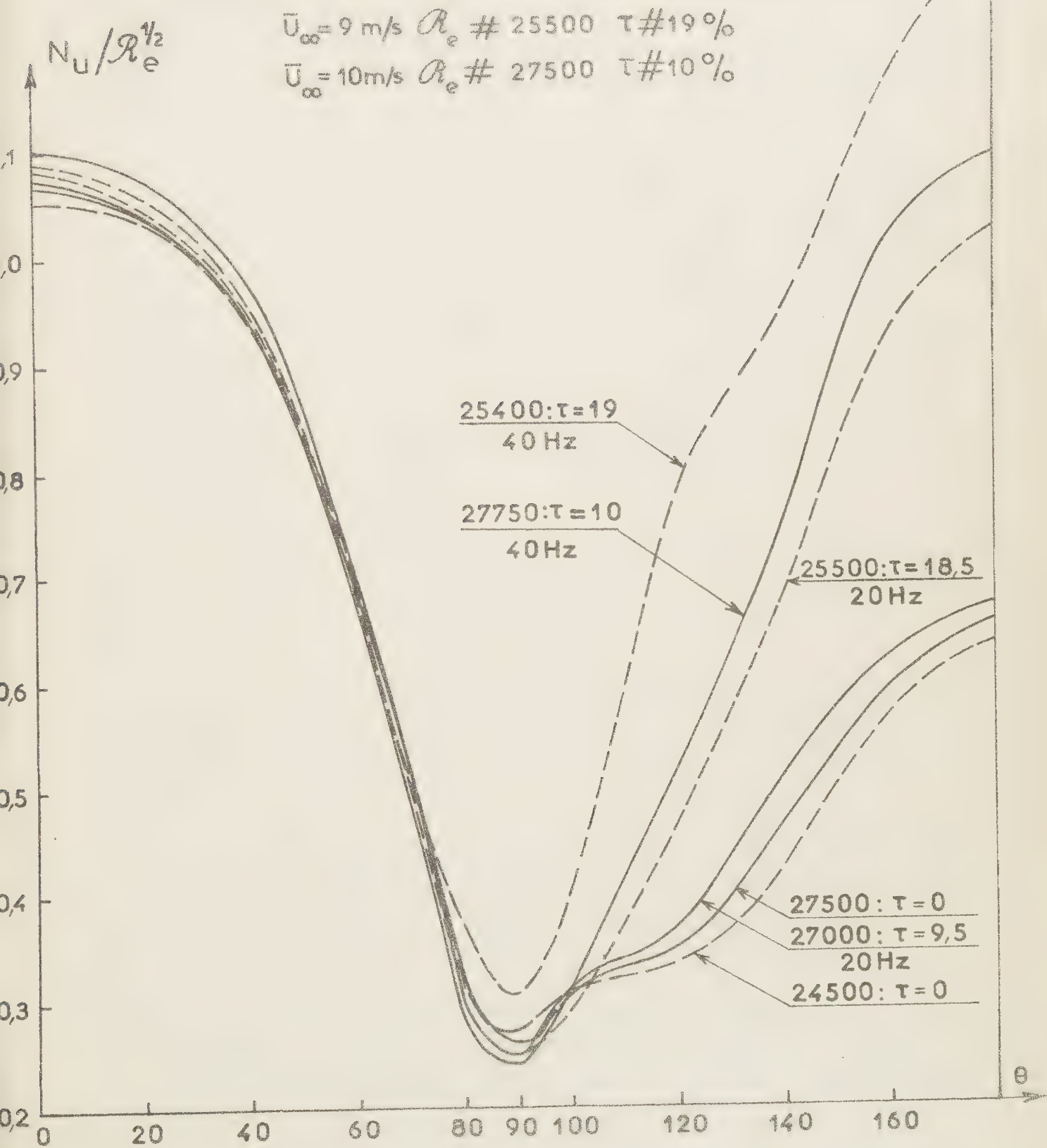


Figure 4

Experiments [2] on a flat plate placed at zero incidence in a pulsating air flow have led to conclusions which can be summarized as follows : in the presence of a boundary layer of stable outline, laminar or turbulent, no increase in heat transfer is attributable to the action of the pulsations as far as our instruments could determine.

b) - In the zones of transition-separation : $80^\circ \leq \theta \leq 100^\circ$ and of wake $\theta \geq 100^\circ$ the pulsations considerably modify the local heat transfer . For the pulsating rates inferior to 20 % a large increase in heat transfer appears in the area surrounding the boundary layer separation point : $\theta \approx 95^\circ$. For higher rates, the pulsating action appears for θ about 80° and it seems that the velocity field in the zone $80^\circ \leq \theta \leq 100^\circ$ is much more disturbed as indicated by the dispersion of the results. However, in every case, the increase in local heat transfer in a pulsating flow appears in the regions of separated boundary layers and is amplified in wake zones where the field of mean velocities has no stable organization.

The gain in local transfer can attain 75 % at the backward stagnation point for $\tau = 28$ %. We note, also, in figure 3 that for $\tau > 17$ % at the mean velocity of 7.25 m/s, the backward stagnation point becomes more active than the forward one.

A dynamic experimental study by exploring the wake with the aid of an anemometric probe confirms the effects of the pulsations on the organization of the wake since we have found that the increase of the pulsating rates reduces the velocity defect in this zone.

- These observations agree with the conclusions of the experiments performed on a flat plate since we have noticed that the zone where the boundary-layer is transitory is the zone where the pulsations have the greatest effect : the heat transfer is multipliable by 3.5

In short, in the separated or unstable boundary-layer regions (zone of transition on a flat plate, and backward face of a cylinder), the gain in heat transfer is very great since it can reach 200 % in the first case and 75 % in the second.

11 - 2 - 2 - Influence of the pulsating frequency

We have proceeded at two series of measurements for $\bar{U}_{\infty} = 9 \text{ m/s}$ and 10 m/s at frequencies of 20 and 40 Hertz.

The examination of the curves in figure 4 leads us to make the following two remarks :

a) - at equal mean velocities and identical pulsating rates less than 10 %, the pulsations at 40 Hertz increase the heat transfer much more than those at 20 Hertz. We find that at 20 Hertz the transfer is only 4 % greater than the transfer at steady flow at the same mean velocity. On the other hand, the same rate at 40 Hertz, renders the transfer curve almost symmetrical, the backward face transferring as much heat as the forward one.

b) - at equal mean velocities and pulsating rates of about 20 %, the increase in pulsations, at 20 and 40 Hertz, becomes very great but we notice a tendency toward saturation of the transfer at 40 Hertz which will be studied in more detail in the following global study.

It appears, however, that the pulsating frequency plays a role in the heat transfer phenomenon.

Conclusions :

The local study we have just made emphasizes the effects of the velocity pulsations on the separated boundary layer zones while showing that the stable boundary-layers are not disturbed. It is fitting now to determine the influential parameters which act upon the transfer phenomenon : however, the experiments using a cylinder permitting local measurements are very long due to the numerous heat equilibriums. For this reason we will pursue our study using the cylinders permitting global measurements. The transfer increases resulting from these experiments will characterize the effects of the pulsations on the heat transfer in separated zones or in the wake since the local study (Figure 3) shows that there is no effect on the forward face in the laminar boundary layer zone.

The global transfer increase express only partially the effect of the pulsations on the wake : a global transfer increase of 30 % for $\tau = 31 \%$ at 10 m/s corresponds in fact to an increase of 75 to 80 % in the separated zone.

III - GLOBAL HEAT TRANSFER

III - 1 - Measurement cylinders

Two cylinders G1 and G2 ($D_1 = 35$ mm and $D_2 = 45$ mm) were used. They consist of one thick copper tube ($e = 10$ mm) designed to assure a good temperature distribution. The tube is heated internally by an electric resistance. End-sleeves avoid aerodynamic singularities and minimize conduction and convection losses on the terminal faces.

The mean temperature is determined by reading the indications of seven thermocouples placed in shallow tin filled axial grooves.

At the heat balance, for which the surface temperature of the cylinder is about $\Delta T_0 = 60^\circ \text{C}$, the Nusselt number is defined as follows :

$$Nu_g = \frac{P - \varphi_p}{\Delta T_0} \quad \frac{1}{\pi L k_f}$$

where P is the electrical power supplied and φ_p the estimated conduction and radiation losses.

III - 2 - Experimental results

The parameters playing an important role in the process of heat transfer by convection in a pulsating flow are :

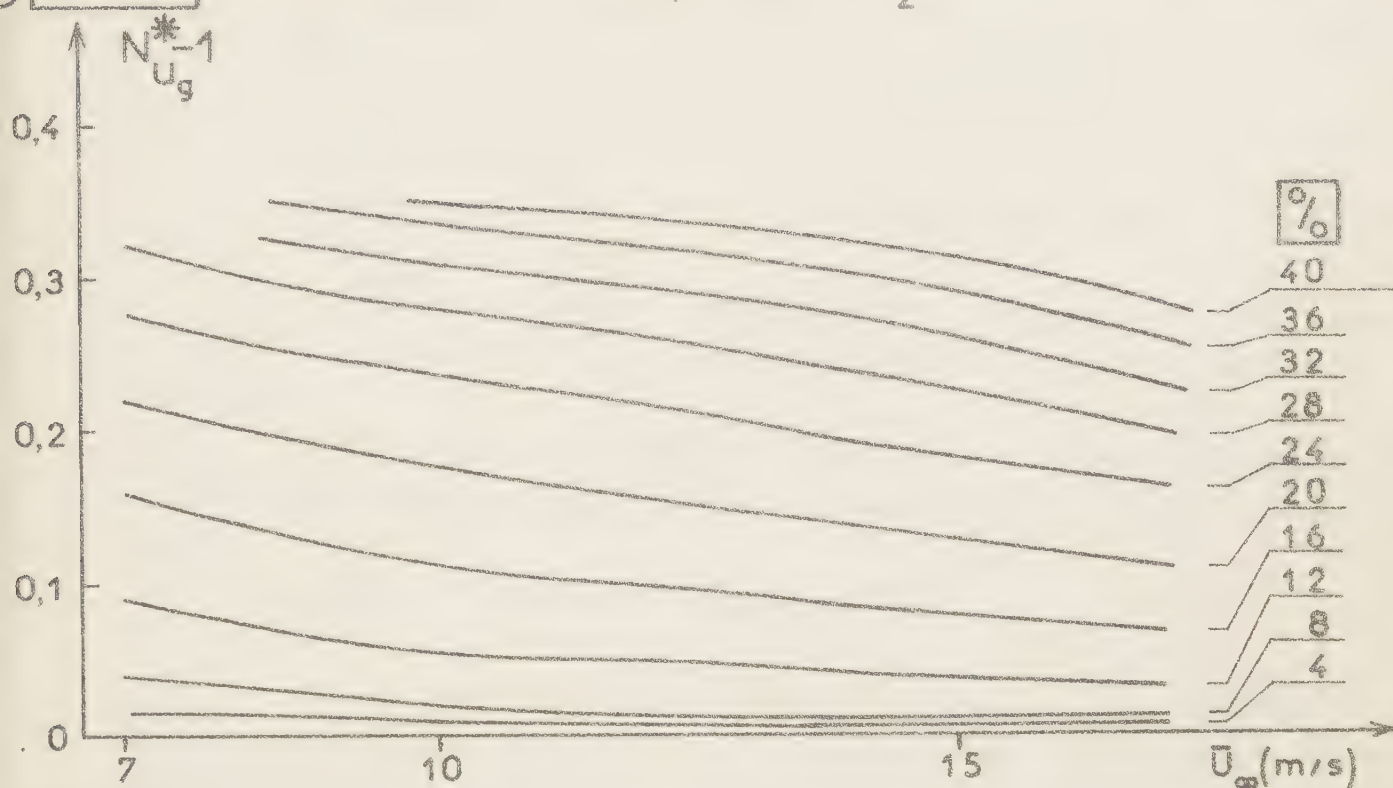
- the diameter of the cylinder : D
- the mean flow velocity : $\bar{U}_\infty$
- the pulsating rate : τ
- the pulsating frequency : f

Of all experiments conducted on cylinder G2, we have limited the study to two series of tests performed at frequencies of 20 and 40 Hertz. Figure 5, (a) and (b) show the relative increase evolution of the transfer as a function of mean velocity. The relative increase of the transfer is defined by : $Nu_g^* - 1$ where

$$Nu_g^* = \frac{Nu_g(\bar{U}_\infty, \tau, f)}{Nu_g(\bar{U}_\infty, 0, 0)}$$

Gain relatif d'échange en écoulement pulsé Cylindre G_2

$f = 20 \text{ Hz}$



$f = 40 \text{ Hz}$

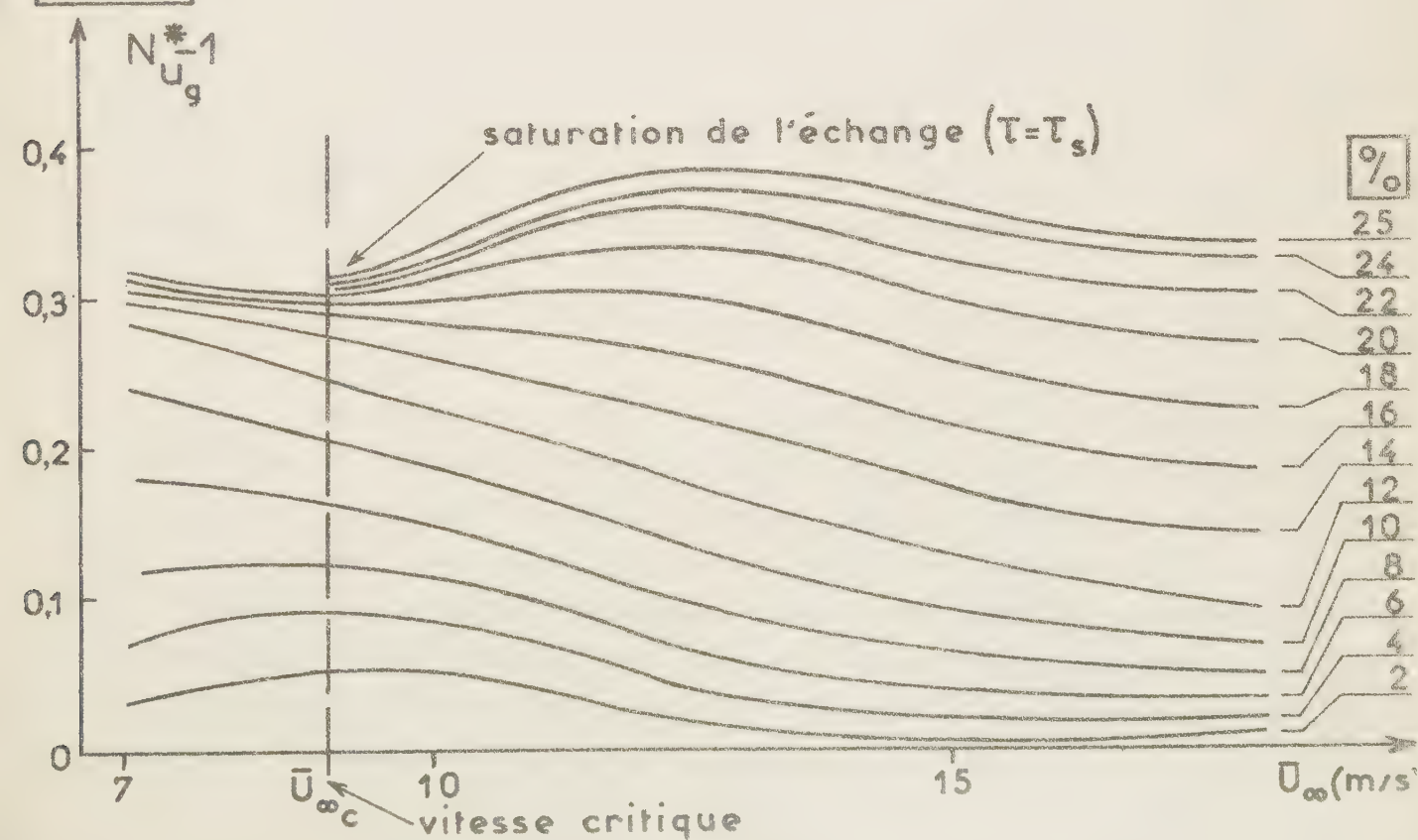


Figure 5

We observe an anomaly at 40 Hertz in the evolution of the global heat transfer as a function of the mean velocity. It is evidenced by :

a) a very clear increase in the transfer to the weak pulsating rates for $7.25 \text{ m/s} \leq \bar{U}_{\infty} \leq 11 \text{ m/s}$.

The increase, which for $\tau = 2\%$ is negligible when $\bar{U}_{\infty} \geq 14.5 \text{ m/s}$, can attain 5% for $\bar{U}_{\infty} = 9 \text{ m/s}$.

b) a tendency toward saturation of the transfer for $\tau \geq 25\%$ and $\bar{U}_{\infty} = 9 \text{ m/s}$. The curves obtained for $\tau = 20\%$; 22% , 24% and 25% also show this phenomenon.

On the other hand, except for the mean velocity range $7.25 \leq \bar{U}_{\infty} \leq 11 \text{ m/s}$ the heat transfer evolution seems to obey the same law at 40 Hertz as at 20 Hertz.

III - 4 - 1 Effect of frequency

In the light of studies conducted by Roshko [3] on the frequency at which vortices are shed for $Re \approx 10^4$, it becomes possible to explain the behavior of the transfer at 40 Hertz for $\bar{U}_{\infty} = 9 \text{ m/s}$. In fact, at this velocity the Strouhal frequency ($f_{st} = S \bar{U}_{\infty} / D$ with $S \approx 0.20$) is 40 Hertz. Therefore, at the velocity $\bar{U}_{\infty}$ such as $f = f_{st}$ "the so-called critical velocity" a resonance phenomenon appears giving way to the particularly great effect of the low-intensity rates and a tendency toward saturation of the heat transfer for $\tau \approx 25\%$.

Systematic experiments from 15 to 45 Hertz confirm the hypothesis of the existence, at the critical velocity, of a resonance phenomenon.

III - 4 - 2 Influence of the pulsating rates at non critical velocities

The curves in figure 6 showing the evolution of the relative transfer increase allow us to ascertain that the maximum sensitivity corresponds to an almost constant relative transfer increase. We can then define a pulsating rate which corresponds, for each mean velocity $\bar{U}_{\infty}$, to the maximal sensitivity rate for which $Nu_g^* - 1$ remains close to 18% . The values taken by the parameter τ_1 , attached to each velocity are shown in figure 6. The introduction of this parameter allows the reduction of the curves obtained for various velocities at 20 and 40 Hertz by carrying as abscissa, the reduced rate τ / τ_1 (fig. 7).

Gain relatif d'échange à 20 Hertz et 40 Hertz : Cylindre G2

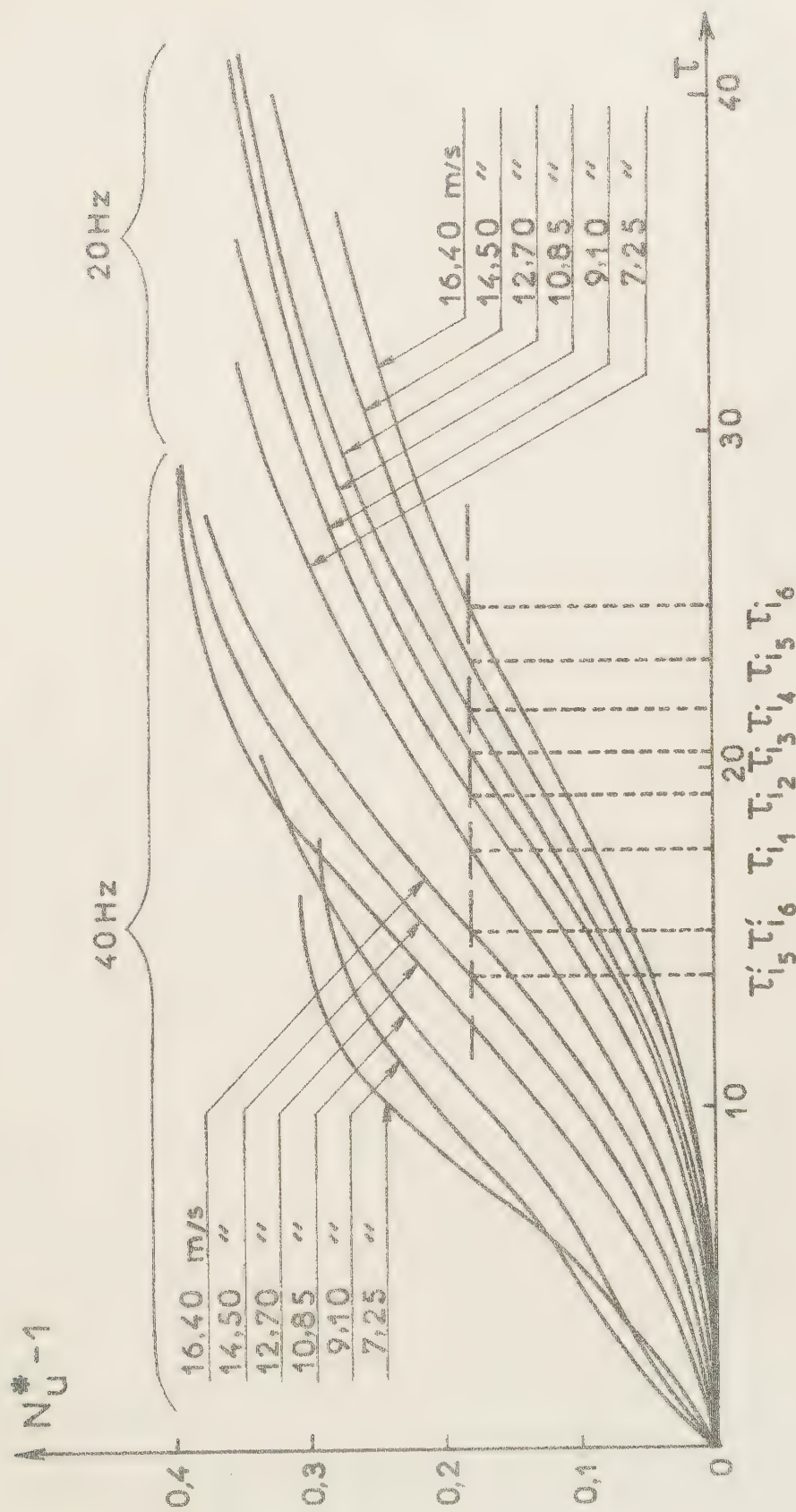


Figure 6

Courbe réduite $NU_g^* - 1 = F(\tau/\tau_i)$

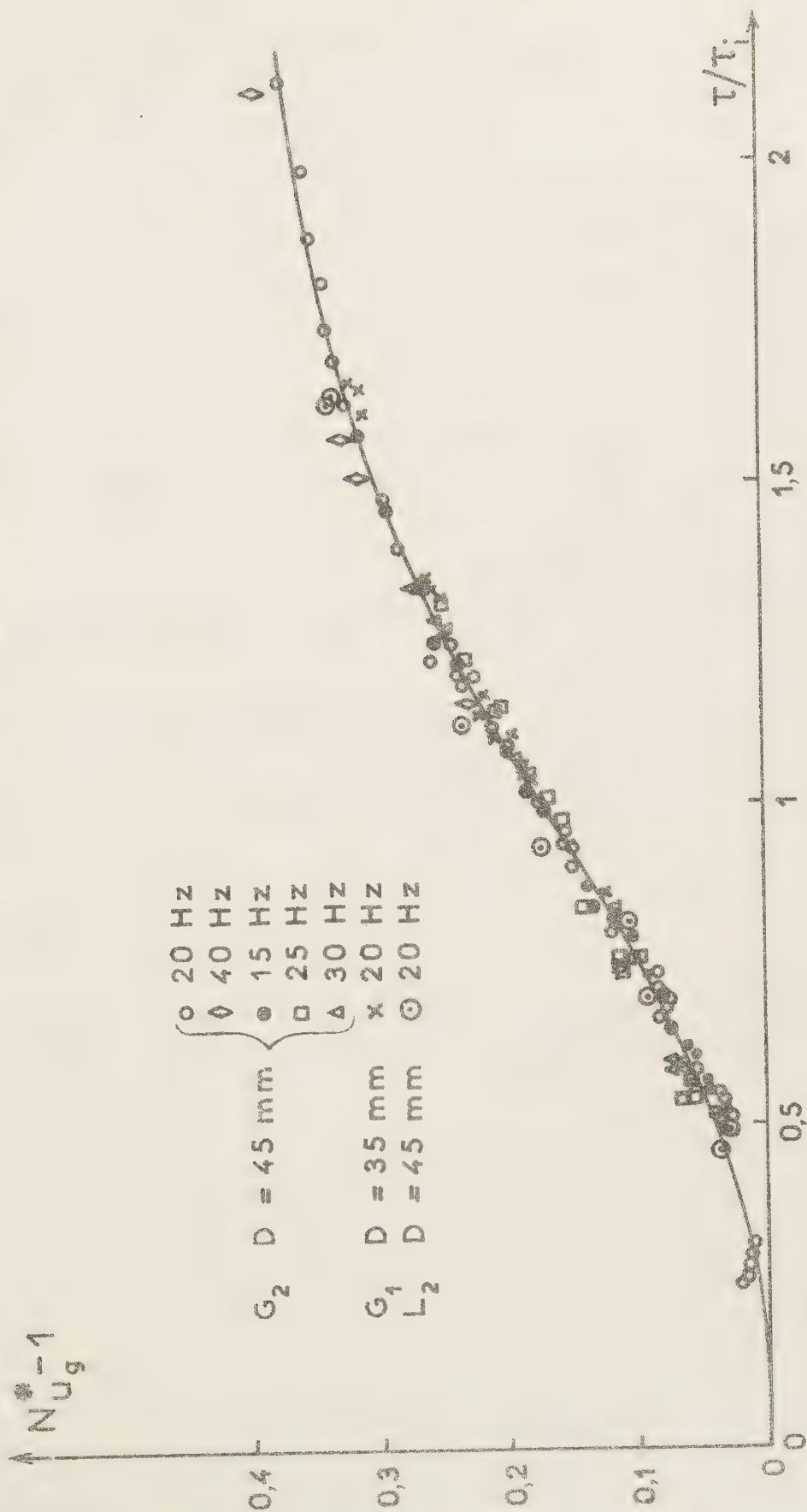


Figure 7

A more complete study reveals the dependence of τ_i :

- on the mean velocity $\bar{U} \propto$
- on the pulsating frequency f
- on the diameter of the cylinder D

Figure 8 shows the evolution of τ_i as a function of $\bar{U} \propto$ for two diameters and five frequencies. The result is the reduction of all the transfer curves to the reduced curve of figure 7 : $Nu = 1 + \mathcal{F}(\tau / \tau_i)$

This reduced curve inspires three remarks :

- for $0 \leq \tau / \tau_i \leq 0.3$ the wake seems inert because the heat transfer remains practically unchanged and the phenomenon thereby differs from the turbulence effect.
- for $0.5 < \tau / \tau_i \leq 1.5$: the transfer grows rapidly to attain its maximum sensitivity for $\tau / \tau_i = 1$. We then notice that $Nu_g^* - 1 \approx 18 \%$.
- for $\tau / \tau_i \geq 1.5$: the effect of the pulsations diminishes and seems to indicate a transfer increase limit of about 36 %.

In summary, the reduced curve $Nu_g^* - 1 = \mathcal{F}(\tau / \tau_i)$ is of great interest in forecasting the transfers by pulsating flow for non-critical mean velocities ; it shows the global effects of pulsations in the separated and wake zones which, alone, are greatly modified.

IV- CONCLUSIONS -

The effect of velocity pulsations on heat transfer by forced convection is unquestionable. However, the particular influence of rate and frequency is very specific and localized.

- on the forward face, the velocity pulsations, according to theory have no sensitive effect on the coefficient of local heat transfer, which always obeys the theoretical transfer law in the absence of pulsations.

- on the backward face, in the separation and wake zones, we have observed two effects :

- ° the first, which we call "frequency effect", takes place at the critical velocity defined by $\bar{U} \propto = f D/S$. Here, we are dealing with a resonance phenomenon characterized by an increase in the effect of pulsations of weak rate $\tau / \tau_i \leq 0.5$ and by a tendency toward transfer saturation for reduced rates above 1.5.

$\tau_i (\bar{U}_\infty)$: f et D sont deux paramètres

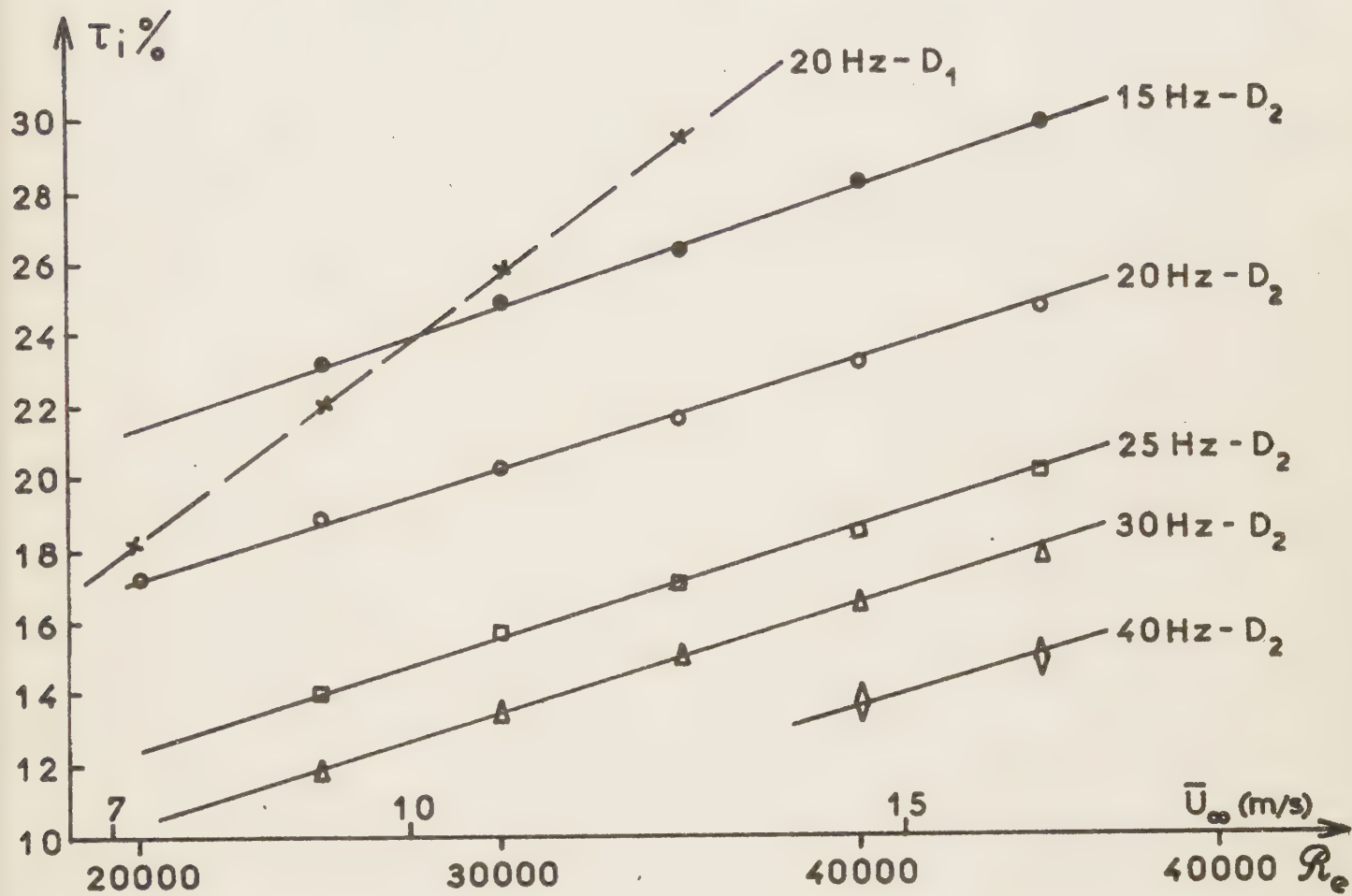


Figure 8

° the second is due for non critical velocity to the action of pulsating rates whose effect on the relative transfer increase is characterized by the reduced curve : $Nu_g^* - 1 = F(\tau/\tau_1)$ and whose practical application may be to forecast the transfer gain in carefully defined conditions of mean velocity rate and frequency.

The comparative studies resulting from experiments conducted at the laboratory on thermal convection by pulsating flow on flat plate at zero incidence and on a cylinder, have allowed us to show the action of velocity pulsations on separated zones or in unstable regions. When the field of mean velocity has an unstable organization (transitory boundary layer on flat plate, separation zone and wake on a cylinder), the effects of the velocity pulsations on the convected thermal transfers are great since they can result in an increase of 200 % in the first case and 75 % in the second, respectively.

The main theoretical difficulty is the choice of the periodic distribution velocity $\tilde{U}_f(x, t)$ outside the boundary layer. A previous experimental study exploring the potential flow in the following form :

$\tilde{U}_f(x, t) = U_f(x) [1 + \epsilon \sin \omega t]$ where $U_f(x)$ is the potential development limited to the first two terms of the Blasius [4] series of a steady flow $\bar{U} \infty$: $U_f(x) = \bar{U} \infty (\beta x^{*2} + \gamma x^{*3})$

It is shown that dynamic solutions (u, v) and thermal solution T^* must obey the following simplified equations :

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$$

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = - \frac{1}{\rho} \frac{\partial p}{\partial x} + \nu \frac{\partial^2 u}{\partial y^2}$$

$$\frac{\partial \tilde{U}}{\partial t} + \tilde{U} \frac{\partial \tilde{U}}{\partial x} = - \frac{1}{\rho} \frac{\partial p}{\partial x}$$

$$\frac{\partial T^*}{\partial t} + u \frac{\partial T^*}{\partial x} + v \frac{\partial T^*}{\partial y} = \frac{k}{\rho C_p} \frac{\partial^2 T^*}{\partial y^2}$$

with limit conditions

$$\begin{aligned} y = 0 & \quad u = v = 0 \quad T^* = 1 \\ y \rightarrow y_f & \quad u \rightarrow \tilde{U}_f(x, t) \quad T^* = 0 \end{aligned}$$

The global solutions (u,v) and T^* are expanded in terms of ϵ as follows :

$$(u, v) = (u_0, v_0) + \epsilon (u_1^i, v_1^i) + \epsilon^2 (u_2^i, v_2^i) + \dots$$

$$T^* = T_0^* + \epsilon T_1^{i*} + \epsilon^2 T_2^{i*} + \dots$$

By substituting these expansions into the governing equations and boundary conditions, and by separating terms according to the powers of ϵ^n the following set of simultaneous differential equations is found :

a) - The resolution of the zeroth order system gives the well known Blasius solution [4] of steady state (u_0, v_0) and $T_0^* = T_a^*(\eta) + \gamma / \beta T_b^*(\eta) x^{*2} + \dots$

b) - The first-order system being linear with regard to (u_1^i, v_1^i) ; and T_1^{i*} , it is convenient to adopt complex notations and to write $(u_1^i, v_1^i) = (u_1, v_1) e^{i\omega t}$

$$T_1^* = T_1^* e^{i\omega t}$$

where u_1 , v_1 , T_1^* are complex quantities depending on x and y

Introducing a stream function ψ_1 such as

$$u_1 = \frac{\partial \psi_1}{\partial y} \quad v_1 = - \frac{\partial \psi_1}{\partial x}$$

$\psi_1 = N \bar{U} \propto \left(\frac{v}{\omega}\right)^{1/2}$ where N is a complex function put into the form $N = A + i B$

$$\text{with } \begin{cases} A = \beta x^* G(\lambda, \eta) + \gamma x^{*3} K(\lambda, \eta) \\ B = \beta x^* H(\lambda, \eta) + \gamma x^{*3} L(\lambda, \eta) \end{cases}$$

we obtain, after identification of the terms according to the powers of x^{*n} , a system where λ is the frequency parameter $\lambda = D\omega / \beta \bar{U} \propto$

At the cost of a frequency parameter limitation, $\lambda < 1$, the earlier system can be transformed by a power development of λ^n followed by a term by term identification. This system will finally be reduced to a set of differential equations in η which can be solved successively with limit conditions.

These equations call in universal functions described in tables where η is the parameter.

$$(u_1^i, v_1^i) = (|u_1|, |v_1|) \sin[\omega t + (\varphi_u, \varphi_v)]$$

where $|u_1|, |v_1|, \varphi_u, \varphi_v$ depend on the universal functions, on the coefficients of the flow (β, γ) and on the reduced frequency and abscissa parameters λ and x^* .

In the boundary layer thickness, we observe an excess velocity which has already been noticed in pulsating flows inside tubes and on a flat plate at zero incidence.

The first order temperature solution can be determined in the same way and it is possible to write :

$$T_1^* = |T_1^*| \sin(\omega t + \varphi_T^*) \text{ where } |T_1^*| \text{ and } \varphi_T^* \text{ are dependent on the universal functions, } \beta, \gamma \text{ and } \lambda, x^*.$$

c) - the partial solutions of the second order are composed of steady and periodic solutions, the circular pulsation of the last one being 2ω . The most interesting solution is the steady one because the mean effect in time is different from zero ; they are (u_{20}^i, v_{20}^i) and T_{20}^* .

The resolution process always brings out the universal functions and the applied method is the same as the preceding one.

The second order dynamic and thermal solutions lead us to rectify the steady solutions (u_0, v_0) and T_0^* to obtain the mean solutions.

$$(\bar{u}, \bar{v}) = (u_0 + \epsilon^2 u_{20}', v_0 + \epsilon^2 v_{20}') \\ \bar{T}^* = T_0^* + \epsilon^2 T_{20}'^*$$

It follows that the skin friction on the wall and the local heat transfer are modified in the experimental condition of this work. We can draw two conclusions from this study :

- from the dynamic point of view the mean increase of skin friction on the wall due to velocity pulsations always remains inferior to 2.5 %
- from the thermal point of view, the heat transfer by pulsating air flow in laminar regions, is indifferent to pulsations whatever their rate.

APPENDIX 2

Quality index ratio of heat transfer $f = 20$ Hertz

The quality index ratio of heat transfer can be determined as the ratio of mean heat power convected, P , to mean mechanical power spent P' .

$$J = P/P'.$$

1° - Determination of mechanical power spent, P'

The dynamic power is defined as the mean value in time of the instantaneous product of the flow velocity $\tilde{U}(t)$ and the drag force which is exerted on the cylinder $\tilde{F}(t)$

$$P' = \frac{1}{T} \int_t^{t+T} \tilde{F}(t) \tilde{U}(t) dt$$

Behind the obstructing cylinder suspended in the test section, a sensor connected to the cylinder at the backward stagnation point by a soldered junction rod, transmits an electric force signal. The sensor is a piezoelectric sensor whose charges are transformed by a charge amplifier into tensions proportional to applied forces.

The instantaneous flow velocity is given as a tension signal resulting from the linearization of the signal supplied by the hot-wire anemometer. An analogical multiplier gives the instantaneous product of the force and velocity signals. The mean value in time is obtained, after filtration, by reading a numerical voltmeter.

Figure (9, a) shows the relative variations of the dynamic power spent at different velocities for ventilating the cylinder.

$$P'^* = \frac{P'(\bar{U}_\infty, f, \tau)}{P'(\bar{U}_\infty, 0, 0)}$$

The relative increase of dynamic power spent varies as a function of τ/τ_i . In the same manner as the relative increase in heat transfer. The maximal power sensitivity corresponds to reduced rate equal to 1, however, we observe, beyond $\tau/\tau_i = 1.3$ a difference which can be attributed to a microphonic effect on the cylinder surface, whose action makes $P'^* - 1$ increase to a value greater than unity.

2° - Quality index

The heat transfer evolutions (fig 7) and the known spent dynamic power (fig. 9, a) lead to the reduced quality index J^* for a cylinder of 45 mm diameter and placed in a air pulsating flow whose frequency is 20 Hertz.

$$J^* = \frac{J(\bar{U}_\infty, 20 \text{ Hz}, \tau)}{J_0(\bar{U}_\infty, 0, 0)}$$

The curve in figure (9, b) shows for $\tau/\tau_i > 0.3$ a more rapid evolution for P' than for P . This phenomenon involves a continuous decrease in the index ratio as τ/τ_i increases. It is concluded that J^* equals 2/3 for $\tau/\tau_i = 1.5$

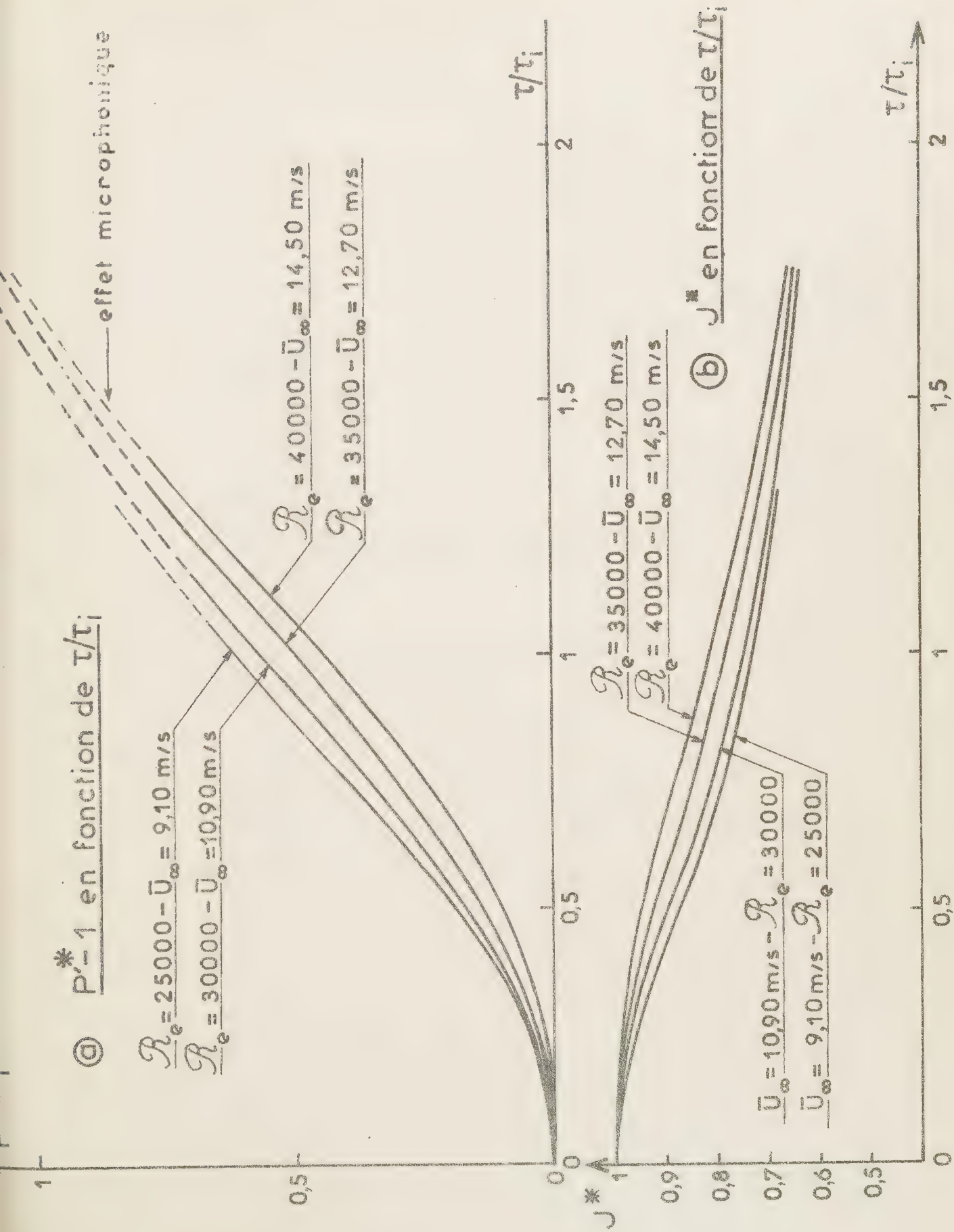


Figure 2

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